

Electron-ion merged-beam experiments at heavy-ion storage rings

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Abstract

In the past two decades, the electron-ion merged-beams technique has extensively been exploited at heavy-ion storage rings equipped with electron coolers for spectroscopic studies of highly charged ions as well as for measuring absolute cross sections and rate coefficients for electron-ion recombination and electron-impact ionization of multiply charged atoms ions. Some recent results are highlighted and future perspectives are pointed out, in particular, in view of novel experimental possibilities at the FAIR facility in Darmstadt and at the Cryogenic Storage Ring at the Max-Planck-Institute for Nuclear Physics in Heidelberg.

Keywords: heavy-ion storage ring; merged-beams method; electron-ion collisions; electron-impact ionization; electron-ion recombination; atomic process in plasmas; highly charged ions

1. Introduction

The electron-ion merged-beams technique has extensively been exploited at heavy-ion storage rings equipped with electron coolers for the study of collisions of free electrons with highly charged ions. Two main lines of research are pursued, i) the spectroscopy of highly charged ions aiming at precise measurements of relativistic, nuclear and QED effects and ii) the determination of reliable absolute rate coefficients of electron-ion recombination and electron impact ionization for applications in astrophysics and fusion research. These fields of research face a bright future with upcoming new facilities such as the Cryogenic Storage Ring (CSR) (Krantz et al. 2011) at the Max-Planck-Institute for Nuclear Physics in Heidelberg, Germany, the TSR at HIE-ISOLDE (Grieser et al. 2012) at CERN in Geneva, Switzerland and the Facility for Antiproton and Ion Research (FAIR) (Stöhlker et al. 2014) in Darmstadt, Germany. A comprehensive overview over the physics of electron-ion collisions has been given Müller (2008). The purpose of the present paper is to highlight recent results and to indicate future opportunities.

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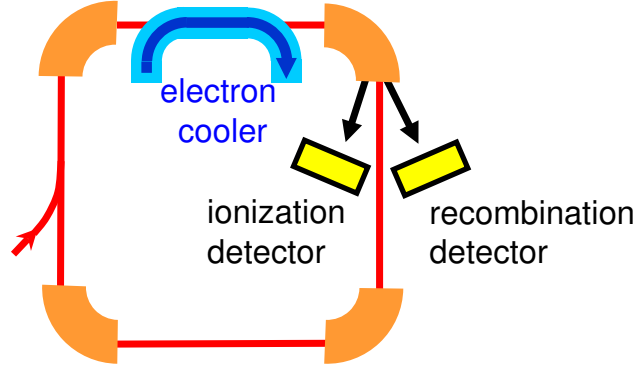


Figure 1: Sketch of the experimental arrangement for electron-ion collision measurements at a heavy-ion storage ring.

2. Experimental technique

Detailed experimental studies of, in particular, electron-ion recombination have become feasible by the implementation of the electron-ion merged-beam technique (Phaneuf et al. 1999) at heavy-ion storage rings which are equipped with electron coolers (Fig. 1, Müller and Wolf 1997, Schuch and Böhm 2007, Schwalm 2007). From an accelerator-physics point of view, electron cooling (Poth 1990) is used to reduce the phase space, i.e., the spatial and momentum spread of the stored ion beam. To this end, in one of the straight sections of the storage ring a cold electron beam is magnetically guided collinearly with the ion beam. When electrons and ions have the same average velocity in the laboratory frame, corresponding to zero electron-ion collision energy in the center-of-mass frame, the hot ions efficiently transfer energy to the cold electrons by Coulomb collisions. For the measurement of photorecombination (PR)



and electron impact ionization (EII)



of an initially q -fold charged atomic ion A^{q+} , the electron energy is detuned from the cooling condition such that nonzero electron-ion collision energies are realized. Since all particles move with high velocity (typically a few percent of the speed of light) the product ions $A^{(q-1)+}$ and $A^{(q+1)+}$ are easily detected by placing single-particle detectors at appropriate locations behind the first storage-ring dipole magnet behind the electron cooler (Fig. 1). Thus, the merged-beam technique makes up for the diluteness of the charged-particle beams by providing a large interaction volume and a detection efficiency of practically 100%. Merged-beams recombination and ionization rate coefficients or cross sections as a function of electron-ion collision energy are readily derived from the measured product-ion count rates by normalizing these on electron current, number of stored primary ions, and beam overlap (Kilgus et al. 1992, Linkemann et al. 1995, Schippers et al. 2001).

The electron-ion merged-beams technique provides access to a wide range of collision-energies extending over several orders of magnitude from sub-meV (Gwinner et al. 2000) to sub-MeV (Bernhardt et al. 2011). Due to the kinematics of the merged-beam arrangement the experimental collision-energy spread is lowest at small collision energies. This feature can be exploited for spectroscopic studies of low-energy recombination resonances, in particular, in combination with an ultracold electron beam from a liquid-nitrogen-cooled photo cathode (Wolf et al. 2006, Lestinsky et al. 2008).

Ion-beam storage lifetimes depend mainly on residual gas density and on ion-velocity (Grieser et al. 2012). Generally lifetimes increase with ion velocity since atomic collision cross-sections decrease strongly with increasing collision energy. When the ion velocity becomes too low electron capture from the residual gas severely shortens the storage lifetime and additionally produces a sizeable background on the recombination detector. In magnetic storage rings, this hampers electron-ion collision experiments with low-charged heavy ions. There is no such limitation in

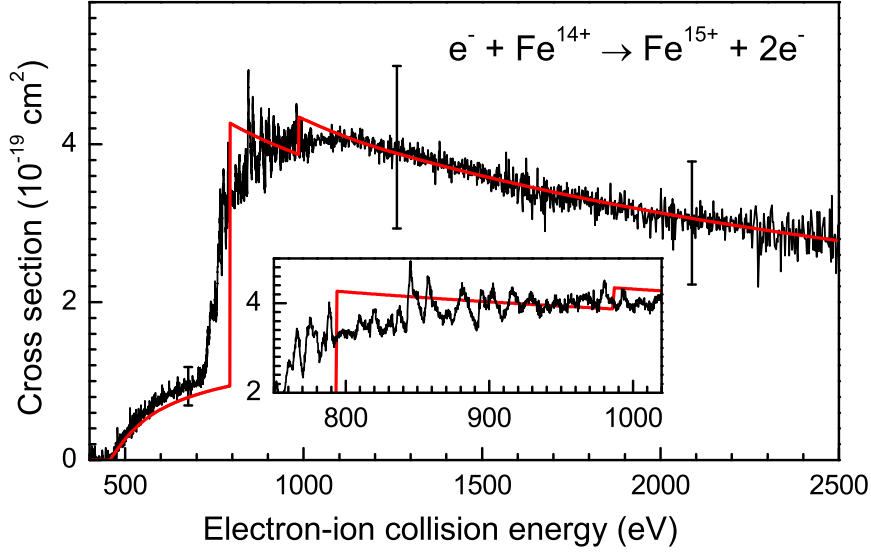


Figure 2: Measured cross section for electron-impact ionization of Fe^{14+} ions (Bernhardt et al. 2014, symbols) in comparison with the most-recent theoretical result (Dere 2007, red full line). The capped error bars denote the systematic experimental uncertainty. The inset provides a detailed view of the strongest ionization resonances.

electrostatic storage rings such as the CSR which will be able to store ions independent of their mass and thus provide access to a wide range of charged particles (Krantz et al. 2011) which could not be investigated before.

3. Atomic data for astrophysics and plasma physics

One line of atomic physics research at heavy ion-storage rings aims at providing accurate atomic data, i.e., absolute cross sections for PR and EII, for applications in astrophysics and plasma physics (for the most recent published results see Mahmood et al. 2013, Hahn et al. 2014, Bernhardt et al. 2014). Since these activities have been repeatedly reviewed before (Savin 2007, Schippers 2009a, Schippers et al. 2010, Schippers 2012, Hahn 2014, Krantz et al. 2014) they are only briefly mentioned here.

The atomic data needs for the modeling of nonequilibrium plasmas are vast. Most of the body of compiled data comes from theory. Collision theory for complex ions requires approximations even with modern computer technology at hand (see also Sec. 4). Therefore, benchmarking by experiment is vital for the further development of the theoretical methods. Much attention has been devoted to PR and EII of iron ions since iron is abundant in many cosmic plasmas. Consequently, prominent iron features are commonly observed, e.g., by space-borne X-ray telescopes (Paerels and Kahn 2003). So far PR and EII cross sections were measured for iron ions with charge states down to $7+$ (Schippers et al. 2010, Schippers 2012, Hahn 2014). Lower charge states which have an increasingly complex electronic structure and for which benchmarking is therefore particularly important will become accessible at the CSR.

A recent example for such benchmarking is the cross section for EII of Fe^{14+} . Figure 2 displays the measured cross section from the TSR and the theoretical cross section from the compilation of Dere (2007). There is overall agreement concerning the gross shape and the magnitude of the cross section. However, there are also significant deviations in particular in the vicinity of the calculated excitation-autoionization steps. These differences are mainly related to the neglect of resonant ionization processes in the calculation (for a detailed discussion see Bernhardt et al. 2014). For a comprehensive theoretical understanding of EII of atomic ions, resonant processes as well as interference effects have to be included in a unified approach (see, e.g., Müller et al. 2014) that goes beyond the widely used independent-processes approximation.

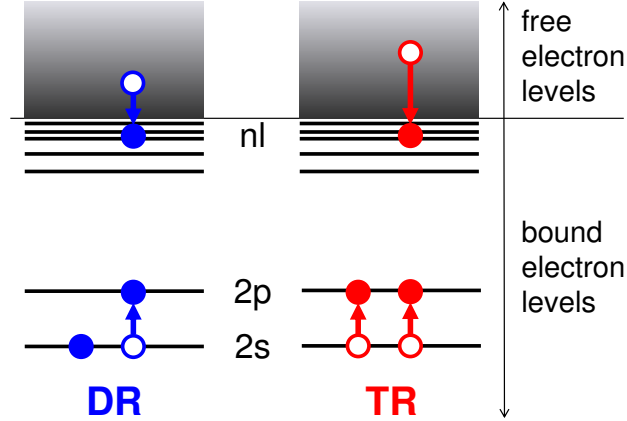


Figure 3: Simplified energy-level diagrams for dielectronic recombination (DR) and trielectronic recombination (TR) of Be-like ions. The K-shell electrons are not shown.

As compared to the single-pass crossed-beams technique (see, e.g., Müller et al. 2014) the storage-ring merged-beam technique offers additional control of the ion beam composition. In a storage-ring, metastable components that often contaminate the ion beam in single-pass experiments can relax to the ground state before data taking starts. For example, no signs of metastable $3s\ 3p\ ^3P$ levels were observed in the storage ring experiment with Mg-like Fe^{14+} of Bernhardt et al. (2014, Fig. 2).

4. Exotic recombination pathways

The most common resonant electron-ion recombination process is dielectronic recombination where the initially free electron excites an initially bound electron and, thereby, loses energy such it becomes bound. This initial step of the DR process is termed dielectronic capture and can be viewed as the time-inverse of the autoionization. It leads to the formation of an intermediate doubly excited state. When this intermediate state decays via photon emission the charge state of the product ion is stabilized and the DR process is completed. Accordingly, the DR cross section is proportional to the initial dielectronic capture rate A_a (autoionization rate) and to the branching ratio for radiative stabilization, i.e.,

$$\sigma \propto A_a \frac{A_r}{A_r + A_a} = \begin{cases} A_r & \text{for } A_r \ll A_a \\ A_a & \text{for } A_r \gg A_a \end{cases} \quad (3)$$

where the limiting cases apply to intermediate levels with large differences between the autoionization rate A_a and the radiative decay rate A_r .

In principle, one can also expect higher order processes where more than two electrons are involved. Such a process is trielectronic recombination (TR) where the incoming electron interacts simultaneously with two initially bound electrons. Figure 3 sketches the TR process in a Be-like ion, where the interaction with the incoming electron may lead to a $2s^2 \rightarrow 2p^2$ core double excitation. TR resonances have first been identified by Schnell et al. (2003, Fig. 4) in a storage-ring recombination measurement with Be-like Cl^{13+} ions. It was found that the contribution of TR to the total recombination rate coefficient is substantial (up to 40%, depending on plasma temperature). This finding, which evidently is relevant for astrophysics has been confirmed by storage-ring measurements with other Be-like ions (Schippers et al. 2004, Fogle et al. 2005, Savin et al. 2006, Orban et al. 2010, Ali et al. 2013). TR has also been observed in electron-ion recombination experiments in an electron-beam ion trap (EBIT, Beilmann et al. 2011, 2013). In these measurements weak signatures of the next-higher-order process, i.e., quadelectronic recombination (QR), were observed as well.

On the theoretical side, higher-order recombination processes may be included by allowing for configuration interactions in the calculations (Schnell et al. 2003, Colgan et al. 2003, Beilmann et al. 2013). This procedure yields

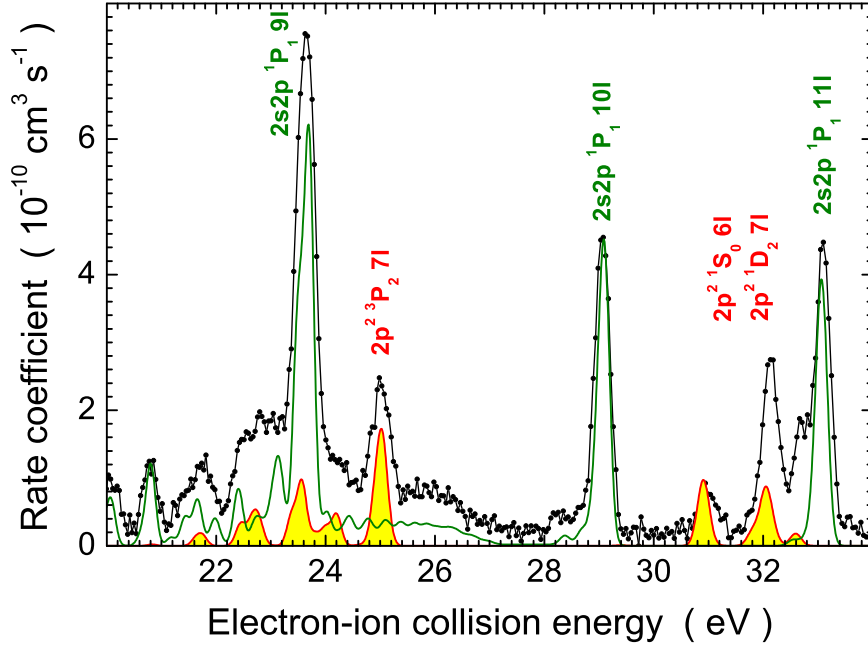


Figure 4: Part of the Cl^{13+} recombination spectrum measured by Schnell et al. (2003, symbols) at the Heidelberg heavy-ion storage ring TSR. Also shown are theoretical results for DR (green full line) and TR (red full line with yellow shading). The designations of some of the identified intermediate DR and TR resonance states are annotating the respective experimental resonance features.

satisfactory results for few-electron ions. For complex many-electron systems, however, the configuration expansions required to incorporate all relevant recombination pathways become prohibitively large. An example, for such a system is the open- $4f$ -shell ion $\text{Au}^{25+}([\text{Kr}] 4d^{10} 4f^8)$. Experimentally, recombination of Au^{25+} has been studied by Hoffknecht et al. (1998) who used a single-pass electron-ion merged-beam approach at the UNILAC linear accelerator at GSI in Darmstadt, Germany. In these experiments an exceptionally large recombination rate coefficient was observed at zero electron-ion collision energy, exceeding the expectation for nonresonant radiative recombination (RR) by more than two orders of magnitude. It was concluded that this excessive recombination rate coefficient is due to mutually overlapping strong recombination resonances.

Subsequent theoretical investigations revealed a large density of multiply excited Au^{24+} resonance levels. The corresponding spacing between levels of same angular momentum and parity was estimated to be about 1 meV for resonance energies below 1 eV (Gribakin et al. 1999). As already mentioned, the explicit inclusion of all these resonance levels in the configuration expansions is not possible due to practical limitations. In this situation Flambaum et al. (2002) have applied statistical theory to electron ion recombination and achieved good agreement with the experimental low-energy recombination rate coefficients for Au^{25+} of Hoffknecht et al. (1998).

In statistical theory (Flambaum et al. 2002), only a limited number of “doorway” resonance levels are considered in the initial dielectronic capture process. Additional resonance levels associated with many-electron interactions are taken into account by mixing, i.e., by performing a weighted average over many adjacent densely spaced levels of the same symmetry from a statistical Breit-Wigner distribution. The mixed-in multiply excited levels are not directly coupled to the target continuum. Therefore, the autoionization rate $A_a^{(m)} \ll A_r$ of the mixed level is smaller than the autoionization rate $A_a^{(d)} \gg A_r$ of the doorway level. Consequently, the resonance cross section (Eq.3) changes from $\sigma \propto A_a^{(d)} A_r / (A_r + A_a^{(d)}) \propto A_r$ to $\sigma \propto A_a^{(d)} A_r / (A_r + A_a^{(m)}) \propto A_a^{(d)}$. Thus, the mixing of the statistically distributed levels increases the resonance cross section by a factor $A_a^{(d)} / A_r$ as explained in more detail by Badnell et al. (2012).

Figure 5 summarizes the state-of-the-art for electron-ion recombination of $\text{W}^{20+}([\text{Kr}] 4d^{10} 4f^8)$. As in the case of isoelectronic Au^{25+} , the measured merged-beam rate coefficient (Schippers et al. 2011) at low electron-ion collision energies is more than two orders of magnitude larger than the theoretical rate coefficient for RR. Up to energies

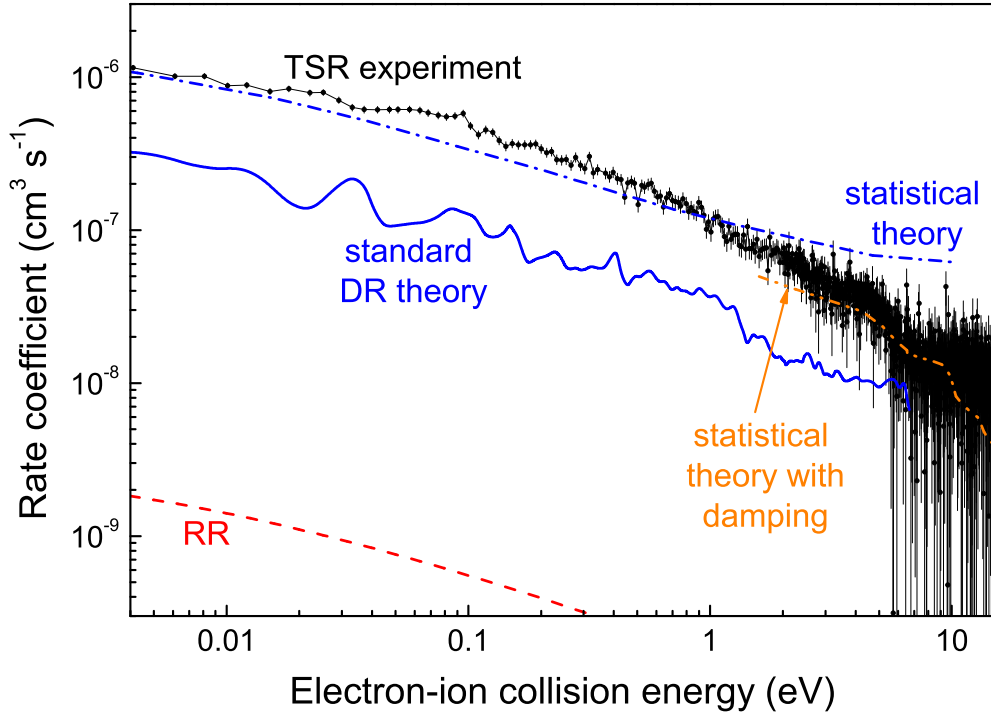


Figure 5: Merged-beams rate coefficients for recombination of $W^{20+}([Kr] 4d^{10} 4f^8)$ ions with free electrons. Symbols denote experimental results of Schippers et al. (2011) from the TSR storage ring. In the displayed energy range it is almost three orders of magnitude larger than the theoretical rate coefficient for radiative recombination (RR, red dashed line, from Schippers et al. 2011). The blue full line and the blue dash-dotted line are the results of standard DR theory and of undamped statistical theory, respectively, from Badnell et al. (2012). The orange dash-dot-dotted line is the results of the damped statistical theory of Dzuba et al. (2013). It should be noted that accurate rate coefficients for the recombination of tungsten ions are of immediate interest for the fusion community, since tungsten is the material of choice for plasma facing components in the ITER tokamak (Pitts et al. 2013). Accurate atomic data are required for the modeling of radiation losses from the fusion plasma due to impurity ions, and recombination rate coefficients for tungsten ions are of particular concern (Pütterich et al. 2008). For W^{20+} (Schippers et al. 2011, Krantz et al. 2014) and W^{18+} (Spruck et al. 2014) it was found that in the temperature ranges where these ions form in a collisionally ionized plasma the experimentally derived plasma recombination rate coefficients exceed the ones from the ADAS atomic data base (ADAS 2014) by up to an order of magnitude.

below ~ 10 eV the result of the standard DR calculation of Badnell et al. (2012, full curve) is a factor of three lower than the experimental curve. When statistical mixing is included the theoretical result agrees with the experimental low-energy rate coefficient (Badnell et al. 2012, dash-dotted curve). A similar agreement between experiment and statistical theory for W^{20+} was also found by Dzuba et al. (2012). However, both theoretical results overestimate the experimental rate coefficient at energies above ~ 1 eV. This is due to the neglect of autoionization of resonance states to excited final levels. These deexcitation channels open up at higher electron-ion collision energies and lead to a reduction of the fluorescence yield. When including this damping effect into statistical theory good agreement with the experimental result is also achieved at higher electron-ion collision energies (Dzuba et al. 2013, dash-dot-dotted curve in Fig. 5). Even better agreement between experiment and statistical theory with damping has been recently established for recombination of $W^{18+}([Kr] 4d^{10} 4f^{10})$ (Spruck et al. 2014). Clearly, the fruitful interplay between experiment and theory has advanced our understanding of electron-ion recombination of complex ions.

Complex atomic and molecular systems also exhibit collective phenomena. For example the cross section for photoionization of xenon atoms (West and Morton 1978) is dominated by a “giant” resonance that is associated with the collective excitation of all $4d$ electrons. Since photoionization is the time inverse of photorecombination, recombination may also proceed via collective excitations. This recombination pathway can be expected to be significant in low-charged heavy ions similar to the process of polarization recombination (Bureyeva and Lisitsa 1998, Korol et al. 2006). As already mentioned above, recombination studies with such ions will become feasible in the Heidelberg

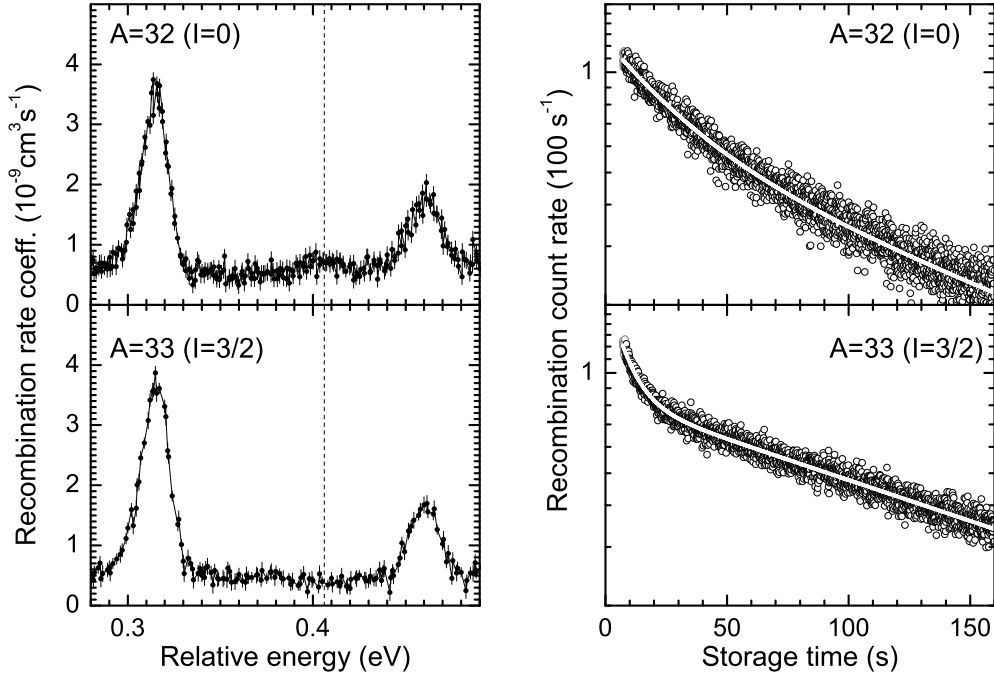


Figure 6: Left: Measured recombination spectra (Schippers et al. 2012) for $^{32}\text{S}^{12+}$ and $^{33}\text{S}^{12+}$ ions, with nuclear spins $I = 0$ and $I = 3/2$, respectively. A dielectronic recombination resonance at ~ 0.4 eV (vertical dashed line) that is excited from the metastable $1s^2 2s 2p \ ^3P_0$ level is not visible in the $^{33}\text{S}^{12+}$ spectrum, since the 3P_0 state is quenched by the hyperfine interaction after sufficiently long storage times. Only resonances that are excited from the $1s^2 2s^2 \ ^1S_0$ ground level occur in both spectra. Right: Measured (symbols) and fitted (lines) decay curves (Schippers et al. 2012) for $^{32}\text{S}^{12+}$ and $^{33}\text{S}^{12+}$ ions stored in the TSR heavy-ion storage ring. The monitored signal is the S^{11+} production rate at an electron-ion collision energy of 0.406 eV (marked by the vertical dashed line in the left panel). In contrast to the $A = 32$ (upper) curve the $A = 33$ (lower) curve exhibits a fast decaying component which is the signature of the hyperfine induced $2s 2p \ ^3P_0 \rightarrow 2s^2 \ ^1S_0$ transition. For this transition a transition rate of $0.096(4) \text{ s}^{-1}$ was derived from the measured decay curves (Schippers et al. 2012). The figure has been taken from (Schippers 2013).

CSR storage ring. In addition, even more heavy species will become accessible such as (endohedral) fullerene ions which also exhibit strong collective photoionization resonances (Scully et al. 2005, Phaneuf et al. 2013, and references therein).

5. Electron-ion collision spectroscopy of highly charged ions

In general, recombination resonance features can be exploited for atomic spectroscopy of multiply excited states. It should be noted that this experimental technique, which may be referred to as “electron-ion collision spectroscopy” does not involve the excitation by or the detection of any photon (Brandau et al. 2010, see also Sec. 2). Recent related experiments (see also Schippers 2009b) comprise the determination of hyperfine-structure splittings (Lindroth et al. 2001, Lestinsky et al. 2008) and nuclear charge radii (Brandau et al. 2008) in heavy few electron systems, the quantitative investigation of the influence of the Breit interaction on recombination resonance strength in H-like uranium (Bernhardt et al. 2011), and the spectroscopy of ions with in-flight produced unstable nuclei (Brandau et al. 2013). Such spectroscopy studies will greatly benefit from the installation of CRYRING at the international FAIR facility in Darmstadt, Germany. CRYRING will be coupled to the existing ESR storage-ring (Stöhlker et al. 2014) which will serve as an injector of precooled and decelerated ions. The combination of excellent vacuum conditions with a cold electron beam will facilitate high-resolution spectroscopic studies of highly charged heavy ions and, thus, the investigation of relativistic, QED, and nuclear effects in such systems with unprecedented precision. In addition, the experimental investigation of resonant processes involving nuclear excitations (Palfy 2010) may become feasible.

Electron-ion collision spectroscopy can also be used for measuring atomic transition rates. An example is the measurement of hyperfine induced transition rates in Be-like ions (Schippers et al. 2007, 2012). Here electron-ion

recombination spectroscopy is the only method that provided experimental access to these exotic atomic transitions in multiply and highly charged ions (Schippers 2013). In these experiments the decay of the number of stored ions is monitored by employing electron-ion recombination (Fig. 6). In order to selectively enhance the signal from the metastable $2s\,2p\,^3P_0$ level, the electron-ion collision energy is tuned to a dielectronic recombination resonance associated with this level. An essential feature of this experimental method is the comparison of measured results from different isotopes with zero and nonzero nuclear spin. The method is readily applicable to a wide range of ions. In the future, beams of radioactive nuclei from HIE-ISOLDE may become available at the TSR storage ring (Grieser et al. 2012). Measurements of HFI induced transition rates may then be used for determining nuclear magnetic moments, some of which are still known only imprecisely. In addition, the method may also be used to study other weak atomic decay channels such as two-photon transitions (Bernhardt et al. 2012).

Acknowledgments

The author is indebted to many colleagues who have contributed to the featured research and whose names appear in the list of references below. The author is particularly thankful to Claude Krantz, Alfred Müller, Daniel Wolf Savin and Andreas Wolf for long-standing fruitful scientific collaboration at the TSR storage ring. The featured research has in part be funded by the Deutsche Forschungsgemeinschaft (DFG, contract numbers Schi378/8-1 and Schi378/9-1).

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